Evolution of Neutral Gas at High Redshift – Implications for the Epoch of Galaxy Formation

L. J. Storrie-Lombardi1,* R. G. McMahon1, & M. J. Irwin2

1Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
2Royal Greenwich Observatory, Madingley Road, Cambridge CB3 0EZ

* current address: Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101 USA
email: lisa@ociw.edu (LJSL); rgm@ast.cam.ac.uk (RGM); mike@ast.cam.ac.uk (MJI)

24 August 1996

ABSTRACT

Though observationally rare, damped Lyα absorption systems dominate the mass density of neutral gas in the Universe. Eleven high redshift damped Lyα systems covering 2.8 < z < 4.4 were discovered in 26 QSOs from the APM z>4 QSO Survey, extending these absorption system surveys to the highest redshifts currently possible. Combining our new data set with previous surveys we find that the cosmological mass density in neutral gas, Ωg, does not rise as steeply prior to z ∼ 2 as indicated by previous studies. There is evidence in the observed Ωg for a flattening at z ∼ 2 and a possible turnover at z ∼ 3. When combined with the decline at z > 3.5 in number density per unit redshift of damped systems with column densities log NHI ≥ 21 atoms cm−2, these results point to an epoch at z ∼ 3 prior to which the highest column density damped systems are still forming. We find that over the redshift range 2 < z < 4 the total mass in neutral gas is marginally comparable with the total visible mass in stars in present day galaxies. However, if one considers the total mass visible in stellar disks alone, i.e. excluding galactic bulges, the two values are comparable. We are observing a mass of neutral gas comparable to the mass of visible disk stars. Lanzetta, Wolfe, & Turnshek found that Ω(z ∼ 3.5) was twice Ω(z ∼ 2), implying a much larger amount of star formation must have taken place between z=3.5 and z=2 than is indicated by metallicity studies. This created a ‘cosmic G-dwarf problem’. The more gradual evolution of Ωg we find alleviates this. These results have profound implications for theories of galaxy formation.

Key words: cosmology—galaxies: evolution—galaxies: formation—quasars: absorption lines

1 INTRODUCTION

While the baryonic content of spiral galaxies that are observed in the present epoch is concentrated in stars, in the past this must have been in the form of gas. The principal gaseous component in spiral galaxies is HI which has led to surveys for absorption systems detected by the damped lines they produce (Wolfe et al. 1986 [WTSC]; Lanzetta et al. 1991 [LWTLMH]; Lanzetta, Wolfe, & Turnshek 1995 [LWT], Wolfe et al. 1995). Damped Lyα absorption systems have neutral hydrogen column densities of NHI > 2 × 1020 atoms cm−2 and they dominate the baryonic mass contributed by HI. We extend the earlier work on damped Lyα systems to higher redshifts using twenty-six QSOs from the APM Damped Lyα Survey (Storrie-Lombardi et al. 1996 [SMIH], Storrie-Lombardi, Irwin & McMahon 1996 [SIM]), with eleven candidate or confirmed damped Lyα absorption systems covering the redshift range 2.8 ≤ z ≤ 4.4 (8 with z > 3.5). These data more than triple the redshift path surveyed at z > 3 and allow the first systematic study up to z = 4.7.

2 EVOLUTION OF ΩG – BARYONS IN NEUTRAL GAS

The mean cosmological mass density contributed by Lyα absorbers can be estimated as

\[ \langle \Omega_g \rangle = \frac{H_0 \mu m_H}{c \rho_{\text{crit}}} \int_{N_{\text{min}}}^{\infty} N f(N, z) dN \]  

giving the current mass density in units of the current critical density (LWTLMH), μ is the mean molecular weight of the gas which is taken to be 1.3 (75% H and 25% He by mass), mH is the mass of the hydrogen atom, ρcrit is the current critical mass density, N_{min} is the low end of the HI
column density range being investigated, and \( f(N,z) \) is the column density distribution function. Unfortunately \( f(N,z) \) is not a simple function and its evolution with redshift is difficult to accurately quantify (LWT, SIM). The integral in equation 1 can be estimated using

\[
\int_{N_{\min}}^{\infty} N f(N,z) dN = \frac{\sum_i N_i (\text{HI})}{\Delta X},
\]

(2)

where \( \Delta X \) is the absorption distance interval. The absorption distance \( X \) is used to remove the redshift dependence in the sample and put everything on a comoving coordinate scale. If the population of absorbers is non-evolving (i.e. the product of their space density multiplied by their cross-section does not change with redshift) they have a constant number density per unit absorption distance. In a standard Friedmann universe \( X \) is defined as

\[
X(z) = \begin{cases} \frac{2}{3} [(1+z)^{3/2} - 1] & \text{if } q_0 = 0.5; \\ \frac{2}{3} [(1+z)^{3/2} - 1] & \text{if } q_0 = 0. \end{cases}
\]

(3)

(Bahcall & Peebles 1969; cf. Tytler 1987). The errors in \( \Omega_g \) are also difficult to estimate without knowing \( f(N,z) \). LWTLMH used the standard error in the distribution of \( N_{\text{HI}} \) which yields zero error if all the column densities in a bin are the same. We have estimated the fractional variance in \( \Omega_g \) by comparing the observed distribution of \( f(N,z) \) with the equivalent Poisson sampling process. This gives

\[
\left( \frac{\Delta \Omega_g}{\Omega_g} \right)^2 = \sum_{i=1}^{p} N_i^2 \left( \frac{N_i}{N} \right)^2
\]

(4)

and \( 1/\sqrt{p} \) fractional errors if all the column densities included in a bin are equal. To address uncertainties in \( f(N,z) \) we also calculated a maximum likelihood estimate of the errors in the HI column density. We used the power law with an exponential turnover form of the column density distribution function, i.e. the gamma-distribution from SIM

\[
f(N,z) = \left( \frac{f_*}{N_*} \right) \left( N/N_* \right)^{-\beta} e^{-N/N_*},
\]

(5)

with \( N_* = 21.63 \pm 0.35 \), \( \beta = 1.48 \pm 0.30 \), and \( f_* = 1.77 \times 10^{-2} \). Unlike a pure power law this form has a finite integral mass. The maximum-likelihood estimates of the errors agree well with the fractional variance.

LWT found that \( \Omega_g \) inferred from studies of damped systems rises with increasing redshift for 0.008 < \( z < 3.5 \). For the range 3.0 < \( z < 3.5 \) which included 4 damped systems and was the highest redshift bin in the study, \( \Omega_g \) in the range 3.5 was twice \( \Omega(\approx 2) \). This implied a much larger amount of star formation must have taken place between \( z=3.5 \). For \( z=3.0 \) the mass in stars in present day galaxies (\( \Omega_{\text{star}} \)) for \( q_0=0.5 \) is the value inferred from 21 cm emission from local galaxies (Fall & Pei 1993; Rao & Briggs 1993). The most striking result is that for \( \Omega_g \) does not rise as steeply prior to \( z=2 \) as indicated by previous studies. There is now evidence for a flattening in \( \Omega_g \) at z≈2 and a possible turnover at \( z≈3 \). This result, combined with the decline at \( z>3.5 \) in number density per unit redshift of damped systems with column densities \( \log N_{\text{HI}} \geq 21 \) atoms cm\(^{-2} \) (SIM) points to an epoch at \( z \approx 3 \) prior to which the largest damped systems are still forming. The decrease in number density at high redshift of the highest column density absorbers is in marked contrast to the more numerous lower column density systems, e.g. Lyman-limit systems (\( N_{\text{HI}} \sim 10^{18} \) atoms cm\(^{-2} \)) (Storrie-Lombardi et al. 1994; Stengler-Larrea et al. 1995) and Ly\( \alpha \) forest absorbers (\( N_{\text{HI}} \sim 10^{13} \sim 10^{15} \) cm\(^{-2} \)) (Williger et al. 1994).

The inclusion of the APM survey data for \( z > 3 \) reduces significantly the value previously found for \( \Omega_g \) in the bin \( 3 < z < 3.5 \). Only one damped system is added to the existing four in this redshift range, but the absorption distance is doubled, which comes in to the calculation of \( \Omega_g \) in the denominator in equation 2 (see table 2). The additional redshift path added by the APM survey is shown graphically by the sensitivity function in figure 6 of SIMH. We find that over the redshift range \( 2 < z < 4 \) the total mass in neutral gas (\( \Omega_g \)) is marginally comparable with the total visible mass in stars in present day galaxies (\( \Omega_{\text{star}} \)). However, if one considers the total mass visible in stellar disks alone, i.e. excluding galactic bulges, the two values are comparable. Using the result from Schechter & Dressler (1987) that galactic disks and bulges contribute equally to the mass density of the Universe, we are observing a mass of neutral gas comparable to the mass of visible disk stars, i.e. \( \Omega_g \sim \Omega_{\text{disk}} \). We note that the uncertainty in the total mass in visible stars in the local Universe is comparable with our estimates of the mass in neutral gas at \( z > 2 \). Given this, and the fact that we do not know if damped systems are the precursors to galactic disks, bulges, or both, these results are difficult to interpret. If we make a plausible correction for obscuration by dust as advocated by Pei & Fall (1995) the \( \Omega_g \) points shown in figure 1(b) would migrate to the po-

* Excluding the new APM data effectively yields the data set analyzed in LWT.
sitions of the open circles shown in figure 2. More work is needed to determine the severity of dust obscuration in optically selected QSO surveys. An estimated 20% correction for the neutral gas not in damped Lyα systems is shown by the open squares.

3 IMPLICATIONS FOR GALAXY FORMATION THEORIES

The shape of the Ωρ curve has been used by numerous authors to constrain theories of galaxy formation and cosmological models (Klypin et al. 1995; Kauffmann & Charlot 1994; Ma & Bertschinger 1994; Mo & Miralde-Escudé 1994). They have found that cold-hot dark matter (CHDM) models are incompatible with the previous results from the damped Lyα systems at z~3 as they predict too few galactic halos. These models need to be reevaluated now that damped Lyα systems are incompatible with the previous results from the 1994). They have found that cold+hot dark matter (CHDM) gas, Ωρ extends studies of the cosmological mass density in neutral gas, Ων, versus a flattening in the Ωρ curve, larger samples of bright z > 3.5 quasars are needed to discover damped Lyα systems with z > 3.

We thank the PATT for time awarded to do the observations with the William Herschel Telescope that made this work possible. We thank the referee, Ken Lanzetta, for his comments.

REFERENCES

Stengler-Larrea E.A., et al., Boksenberg A., Steidel C.C.,
Sargent W.L.W., Bahcall J.N., Bergeron J., Hartig G.F., Januzzi B.T., Kirkhakos S., Savage B.D., Schneider D.P.,
Table 1. Data for Figures

<table>
<thead>
<tr>
<th>Redshift Range</th>
<th>DLA # of</th>
<th>QSO in bin</th>
<th>DLA QSO</th>
<th>(\Delta z)</th>
<th>DLA</th>
<th>QSO (\Delta X)</th>
<th>(\Omega_g) (\Delta X)</th>
<th>(\Omega_g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008-1.5</td>
<td>0.64</td>
<td>47.8</td>
<td>4</td>
<td>186</td>
<td>73.1</td>
<td>0.56±0.32</td>
<td>58.5</td>
<td>0.70±0.40</td>
</tr>
<tr>
<td>1.5-2.0</td>
<td>1.89</td>
<td>27.9</td>
<td>4</td>
<td>126</td>
<td>79.5</td>
<td>1.21±0.71</td>
<td>47.1</td>
<td>2.05±1.19</td>
</tr>
<tr>
<td>2.0-3.0</td>
<td>2.40</td>
<td>120.2</td>
<td>22</td>
<td>176</td>
<td>415.9</td>
<td>1.50±0.49</td>
<td>223.4</td>
<td>2.79±0.91</td>
</tr>
<tr>
<td>3.0-3.5</td>
<td>3.17</td>
<td>24.3</td>
<td>5</td>
<td>82</td>
<td>102.0</td>
<td>1.48±0.72</td>
<td>49.8</td>
<td>3.04±1.48</td>
</tr>
<tr>
<td>3.5-4.7</td>
<td>4.01</td>
<td>19.2</td>
<td>9</td>
<td>32</td>
<td>93.8</td>
<td>0.85±0.34</td>
<td>42.5</td>
<td>1.87±0.75</td>
</tr>
<tr>
<td>Dashed bins, excluding high redshift data.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0-3.0</td>
<td>2.38</td>
<td>114.6</td>
<td>21</td>
<td>154</td>
<td>394.8</td>
<td>1.56±0.52</td>
<td>212.6</td>
<td>2.90±0.96</td>
</tr>
<tr>
<td>3.0-3.5</td>
<td>3.19</td>
<td>11.8</td>
<td>4</td>
<td>56</td>
<td>48.9</td>
<td>2.79±1.47</td>
<td>24.0</td>
<td>5.68±3.00</td>
</tr>
</tbody>
</table>

Table 2. Redshift Path and Absorption Distance

<table>
<thead>
<tr>
<th>Data Set</th>
<th>(\Delta z)</th>
<th>(\Delta X) ((q_0 = 0))</th>
<th>(\Delta X) ((q_0 = 0.5))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 &lt; z &lt; 3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APM Damped Ly(\alpha) Survey</td>
<td>12.5</td>
<td>53.1</td>
<td>25.8</td>
</tr>
<tr>
<td>WTSC + LWTLMH + LWT</td>
<td>11.8</td>
<td>48.9</td>
<td>24.0</td>
</tr>
<tr>
<td>Combined</td>
<td>24.3</td>
<td>102.0</td>
<td>49.8</td>
</tr>
<tr>
<td>z &gt; 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APM Damped Ly(\alpha) Survey</td>
<td>30.5</td>
<td>141.2</td>
<td>65.5</td>
</tr>
<tr>
<td>WTSC + LWTLMH + LWT</td>
<td>13.0</td>
<td>54.6</td>
<td>26.7</td>
</tr>
<tr>
<td>Combined</td>
<td>43.5</td>
<td>195.8</td>
<td>92.2</td>
</tr>
<tr>
<td>0 &lt; z &lt; 4.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APM Damped Ly(\alpha) Survey</td>
<td>36.1</td>
<td>162.3</td>
<td>76.5</td>
</tr>
<tr>
<td>WTSC + LWTLMH + LWT</td>
<td>203.4</td>
<td>602.1</td>
<td>344.8</td>
</tr>
<tr>
<td>Combined</td>
<td>239.5</td>
<td>764.4</td>
<td>421.3</td>
</tr>
</tbody>
</table>

Figure 1. The mean cosmological mass density in neutral gas, \(\Omega_g\), contributed by damped Ly\(\alpha\) absorbers for 0.008 \(\leq z \leq\) 4.7 for (a) \(q_0 = 0\) and (b) \(q_0 = 0.5\). The solid bins include the combined data set and the dashed bins exclude the new APM high redshift data. The region \(\Omega_{\text{star}}\) is the \(\pm 1\sigma\) range for the mass density in stars in nearby galaxies (Gnedin & Ostriker 1992). The point at \(z = 0\) is the value inferred from 21 cm emission from local galaxies (Fall & Pei 1993; Rao & Briggs 1993). These results are tabulated in table 1.

Figure 2. The mean cosmological mass density in neutral gas, \(\Omega_g\), contributed by damped Ly\(\alpha\) absorbers for 0.008 \(\leq z \leq\) 4.7. The solid bins are the combined data set shown in figure 1(b) for \(q_0 = 0.5\). The circles show the observed data points corrected for possible dust obscuration using values determined from the closed-box/outflow models shown in figure 4(b) of Pei & Fall (1995). The squares add an estimated 20% correction for neutral gas not in damped Ly\(\alpha\) absorbers. The region \(\Omega_{\text{star}}\) is the \(\pm 1\sigma\) range for the mass density in stars in nearby galaxies (Gnedin & Ostriker 1992). The point at \(z = 0\) is the value inferred from 21 cm emission from local galaxies (Fall & Pei 1993; Rao & Briggs 1993).